

An Airbreathing Engine for Aerospace Propulsion

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Abstract

Airbreathing engines combined with chemical rockets will be superior as a single stage to orbit propulsion device. A variable cycle engine incorporating interstage reheat and variable bypass ratio supersonic fan, is proposed here for this application. Operating in two modes viz. turbojet and fan turbo ramjet configurations, this airbreathing engine is optimised for high specific impulse. Performance characteristics of this aerospace engine have been evaluated through a computer programme analysis.

Aerospace Propulsion

There have been tremendous strides in the field of aeronautics during this century, both in aerodynamic sciences and flight propulsion. The technological growth has taken the man through heavier than air powered flight and supersonic cruise into rocket propelled earth orbit and beyond. Technological growth in the past had taken place in a stepwise manner to overcome specific barriers. Specific challenges were met with an aim to meet requirements, and not as much of perfecting a technology. One could say technology developments were adhoc and not adaptive. A lot of inroads have been made in the field of aero-propulsion as to require consolidation and amalgamation of these with adaptivity and flexibility. Space science has progressed so much that a unified field known as aerospace propulsion has come into existence, with its own challenges.

Till recently, space technology was developed essentially to go into space with either a remote satellite or a man on the moon with his bare life support. The pay load mass was much smaller and the mass ratio was not at all a criterion so far. The propulsion requirements were simply a high thrust device enclosed in a slender body, which could quickly pass through the subsonic- supersonic flow domain in the atmosphere. Chemical rockets with a constant thrust of a high value fitted this bill and have been used quite successfully. Today space is being turned into a platform for many activities and the goal is to make use of it with a sizeable presence rather than just reaching out. This requires much heavier loads to be transported to space and at regular intervals. Efficiency and optimal use are the new criteria for the propulsion systems to be developed in the future. Space shuttle is obviously a step in this direction. There are two features of the space shuttle concept. One is the earth orbit which is becoming an anchoring stage to any space venture. Another aspect is that the energy expended in reaching this stage is a very significant proportion of total energy requirements for any mission in space. This earth orbit is at a height of 100 to 300 km and requires a velocity of 8 km/s. With chemical rockets whose specific impulse is about 450 s, the mass ratio cannot be brought down lower than 6. And in the context of earth

orbit at 100–300 km, the atmosphere going upto 60 km, is a significant portion of the mission range. In order to decrease the mass ratio and to effectively make use of the flight through atmosphere, it becomes necessary to contemplate the use of airbreathing engines for space vehicles.

Mission Profile to Orbit

For a mission to orbit at 100 km and above it can be shown that a combination of airbreathing and rocket propulsion is far better than a straight rocket propulsion. For one thing, the pay load fraction can be increased nearly twice or more from the 5% level of chemical rockets. It can further be enhanced if the LACE concept is successful and practical. Advantage is taken mainly of utilising the oxygen in the atmosphere and not carrying the oxidiser as in the case of chemical rockets. With oxidiser to fuel ratio of 5, this has a substantial effect. In view of this fact, specific impulse of an airbreathing engine is an order of magnitude higher in the range of 2000–6000 s. The thrust to weight ratio of 10 or so is not an inhibiting factor since the mission profile and the energy expended is predominantly in the atmosphere. As can be seen later the profile can be structured to accommodate the thrust to weight ratio of air breathing engines albeit low.

The incremental velocity given to a vehicle is

$$\Delta V = g I_{sp} \ln (M_r) - g \cos \theta \left[1 - \frac{1}{M_r} \right] \frac{I_{sp}}{F/M_0}$$

For an orbit mission, the incremental velocity required is 8 km/s at 100 km or so. Out of this 4 km/s increment is imparted to the vehicle in the atmosphere within 60 km altitude. Turbojet engines of today operate upto 30 km altitude to attain a flight speed of 1 km/s or Mach 3. Further acceleration and climb is possible through Ramjet/Scramjet which are also airbreathing engines. Various options combining the turbojet with ramjet, scramjet, LACE and chemical rocket are being studied in boosting the vehicle to orbit from 30 km altitude and Mach 3 speed. All these studies and the mission performance largely depend on the type of airbreathing engine that is employed to bring the vehicle to an altitude of 30 km through the atmosphere. Some of the studies include

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a prolonged cruise at this altitude for liquefaction and collection of atmospheric oxygen for subsequent rocket mode operation in the Lace concept¹.

Unlike a rocket engine, specific impulse and thrust of an airbreathing engine varies with altitude and flight conditions. Variation in these parameters for a conventional turbojet engine would not lead to optimum performance of the mission. Additionally, it would restrict the choice of mission profiles due to limitation of engine operation at off design points during parts of the mission. These lead to the conclusion that a range of propulsion devices may be needed or ideally that a given type of thrust device could be made to perform in variable modes of operation optimising specific impulse. In the context various engine options have been studied for supersonic cruise aircraft². There is a lot of advantage to be gained in building variable geometry into the engine for high speed propulsion^{3,4,5}. If full advantage is to be taken of an airbreathing turbojet engine for aerospace propulsion, it has to be a variable cycle engine capable of being adapted as a straight turbojet near sonic speed and a supersonic fan ramjet at the far end of flight speed and altitude. It is this adaptivity and flexibility that will make the application of airbreathing engine to aerospace propulsion a success.

An Airbreathing Engine Concept

The foregoing discussions suggest that an airbreathing engine for aerospace propulsion should be able to provide a controlled thrust at all flight Mach numbers and altitudes along with an optimised specific impulse. For a turbojet specific impulse and thrust per unit frontal area are functions of temperature and pressure ratio employed in the aero-thermodynamic cycle. Additionally, a conventional engine will have a fixed characteristic variation of these depending on flight speed and altitude. A straight turbojet is suited for operation near sonic speeds in lower atmosphere. However at high supersonic speeds, the ram pressure is sufficiently large that the engine cycle pressure ratio needs to be curtailed to that of the fan pressure ratio alone. When the Mach number exceeds 3, the fan pressure ratio itself will have to be lowered. This indicates that an afterburning turbofan, with increasing bypass ratio, would be the suitable engine for operation at higher supersonic speeds and altitude.

To avail the above cycle characteristics of an airbreathing engine, it is imperative that bypass mass flow should be variable and there should be provision for attaining heat addition at higher temperatures. Thus a variable bypass reheat cycle forms the basis of the airbreathing engine concept for aerospace propulsion. Conventional engines employ reheat in the form of an afterburner, which reduces the specific impulse. A reheat in the intermediate stage of the turbine, while augmenting the specific impulse performance, will smoothly merge with other characteristics of the engine. They also provide a variable parameter for matching purpose at different flight conditions. The variation of bypass ratio

and the associated fan pressure ratio will require, apart from variable geometry ducting, variation in fan power drive. The configuration that is conceived above seeks to add as much of heat as possible at higher temperature levels, which improves the efficiency. This would require more components operating at elevated temperatures. Progress in development of new materials should alleviate this problem. High strength ceramic composites would become available for use in hot environs of the engine. In this context, designing for long life may be substituted by expendable hot components to be moulded at cheaper cost and replaced at periodic intervals. This idea will enable the introduction or more appropriately re-introduction of radial turbomachinery at the hot centre of the engine. With recent advances in radial turbomachines, it is definitely conceivable that the high pressure spool will consist of centrifugal compressor followed by a radial turbine, similar to a turbocharger. Such a configuration will provide sufficient space to accommodate the additional reheat combustion chamber within the engine.

Conceptually the aerospace engine will be as follows:

- * Fully variable geometry intake
- * Front fan stage in the LP spool
- * Variable geometry bypass duct
- * HP spool consisting of
 - * core compressor
 - * reverse flow combustor
 - * core turbine
- * Reheat combustion chamber
- * Fan turbine in LP spool
- * Bypass duct
- * Afterburning in bypass and inner ducts
- * Variable geometry bypass and inner nozzles

Figure 1 and Figure 2 show the configuration of the aerospace engine in its different modes of operation. The leaky turbojet configuration of Figure 1 is used for take off and dash to sonic speed at low altitude. The engine is operated as a conventional turbojet. However, reheat in the intermediate stage is employed instead of afterburning. This will enhance the specific impulse characteristic. As the vehicle gains supersonic flight speeds and climbs to higher altitudes, the fan turbo ram configuration of Figure 2 is brought into operation. In this mode, the bypass ratio of the fan is progressively increased to a high value. This is effected through movement of baffles behind the fan stage. They deflect part of fan outlet flow into the bypass ramjet duct, in which ramjet combustion switched on. Afterburning of the core flow is also resorted to in order to keep the thrust at a high level. This manoeuvre reduces the back pressure on the fan and hence the cycle pressure ratio of the ramjet flow in the bypass duct is moderated to optimum value. When the

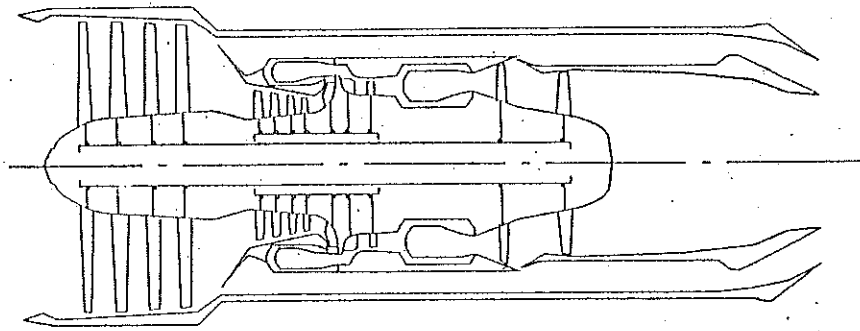


Fig. 1 Aerospace engine -- Turbojet mode

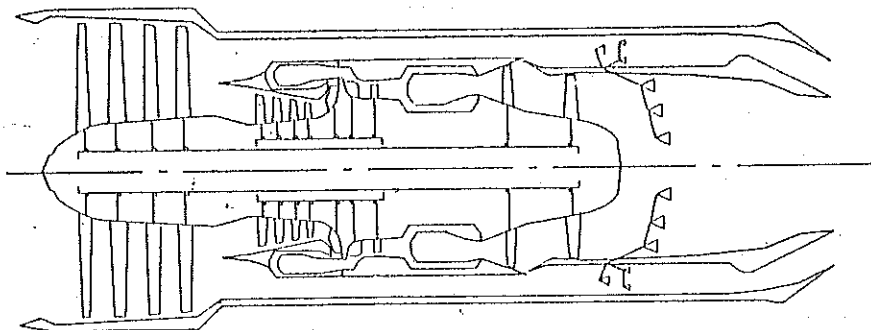


Fig. 2 Aerospace Engine-Fan-Turbo-Ram Jet Mode

flight speed increases beyond Mach 2, the fan pressure ratio is further reduced through a pre-programmed control. Beyond Mach 4, the fan pressure rise requirement is very small and the engine develops its thrust essentially as a ramjet upto Mach 6. The fan however is designed to cope with flight speed corresponding to Mach 6 at altitudes between 30 and 40 km. A suitable air intake system with variable geometry is assumed to be provided for this purpose. The variable geometry of the intake will be optimised for a range of flight speed extending upto Mach 6 from internal aerodynamic and engine cycle considerations. An essential feature of combining these two modes of operation is that the performance of an airbreathing turboengine has been stretched to encompass ramjet propulsion. Specific impulse is optimised in both modes.

This aerospace engine unifies turbojet and fan ramjet modes of operation in an airbreathing configuration for propelling an aerospace vehicle to a flight speed of 1.8 km/s namely Mach 6 and to an altitude of 40 km. At this point onwards a rocket engine could take the vehicle either straightaway to orbit or through an intermediate scramjet operation upto a flight speed of 4 km/s and an altitude of 60 km.

Performance Characteristics

The conceptual design of the futuristic aerospace engine was evaluated for its aero-thermodynamic performance. It was

carried out through a theoretical analysis using an iterative computer programme. Initially, the design point and ambient conditions were chosen along with fan temperature rise, compressor pressure rise, combustion temperature, bypass ratio, etc. The programme was iterated through analysis for a desired performance namely specific thrust by varying the combination of above parameters. Once these were fixed, the design point characteristic parameters of each component of the engine were calculated and geometric dimensions at critical points sized to the required thrust. For part load or off design analysis, the engine component parameters were balanced for power, speed and mass flow. Realistic efficiency levels and off design parametric performance characteristics for each component such as intake, compressor, combustion chamber and nozzle were assumed theoretically. Variation in the value of these parameters for changes in flight speed and altitude conditions are taken into consideration. During analysis, for every point at off design, component parameters were calculated in an iterative manner to satisfy the governing equations for engine balance. In this way engine characteristics were obtained throughout the entire operational range of the flight envelope. For the above analysis turbine entry temperature both from the main and reheat combustion chambers were limited to 1660 K while afterburning temperature was held at 2060 K. The simplified flow chart of the computer programme is shown in Figure 3.

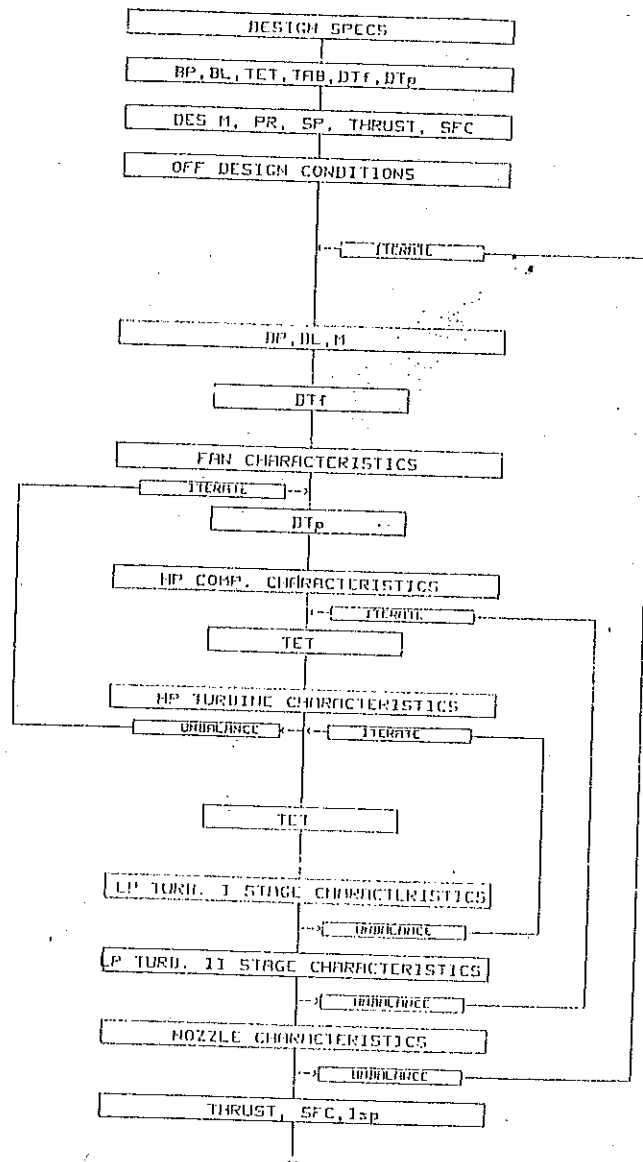


Fig. 3 Computer program flow chart

Performance characteristics of the engine cycle through the range of a mission profile were predicted in the form of specific impulse and thrust per unit fan frontal area. A typical mission profile was assumed as shown in *Figure 4* giving the altitude with corresponding flight speed. In order to take full advantage of the airbreathing engine, a quick dash to supersonic speeds in low altitude followed by a steep climb and then an accelerating climb to an altitude of 40 km is considered. The specific impulse characteristic of the aerospace engine is shown against flight speed in *Figure 5*. For purposes of comparison similar characteristic for a conventional turbojet and an external ramjet combination is also shown in the same figure. It is clearly seen that there is more than 10% improvement in the specific impulse characteristic for the unified aerospace engine. The improvement is much larger at take off and low speeds upto 0.7 km/s. This has been effected through employment of intermediate stage reheat as opposed to afterburning. A smooth transition takes place through a supersonic fan turbo ramjet mode, during which the fan pressure ratio is gradually reduced by increasing the bypass ratio. Fan pressure ratio is varied from 3.6 at take off to 1.1 at high supersonic speeds. This helps in keeping the specific impulse high and stretching the operation of turbo engine mode to flight speeds of 1.6 km/s. It is seen that specific impulse values exceeding 6000 is possible. During most part of the mission the value is above 3000. This is better than most of the engine options investigated by others⁶. In *Figure 6*, the thrust per unit fan frontal area for both the conventional turbojet and the unified aerospace engine are given. Here again one can see improvement in performance for the unified aerospace engine, a straight drop in thrust seen at take off and low speeds, is due to the absence of afterburning and restriction of reheat temperature. As seen in the launch profile the mission has a horizontal take off and acceleration with moderate climb. The high specific impulse realised at this low altitude and flight speeds will be of a larger benefit in optimising the mission performance.

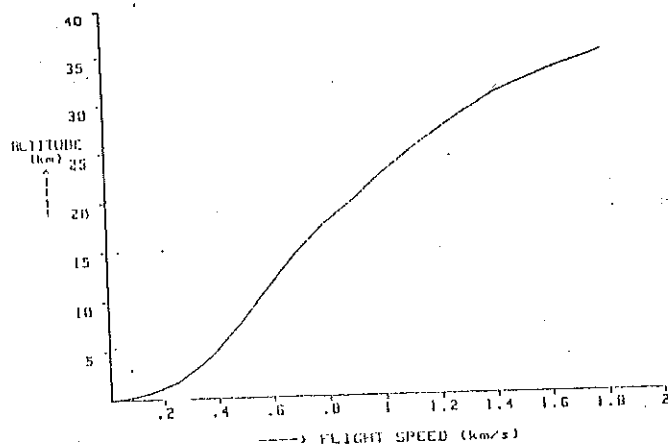


Fig. 4 Launch profile

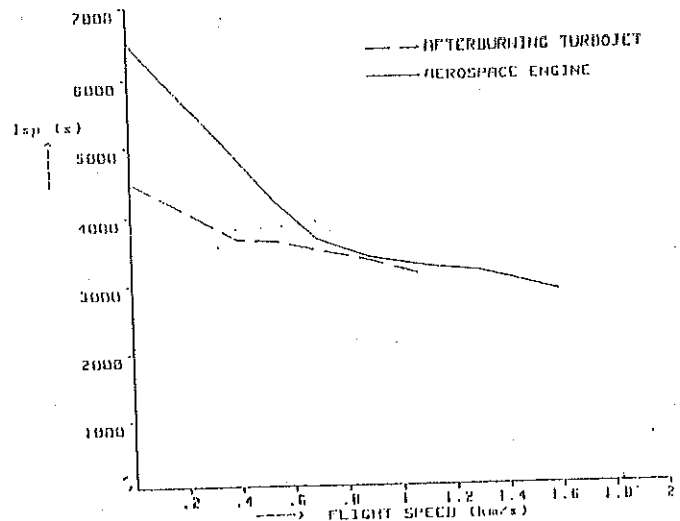


Fig. 5 Specific impulse characteristics

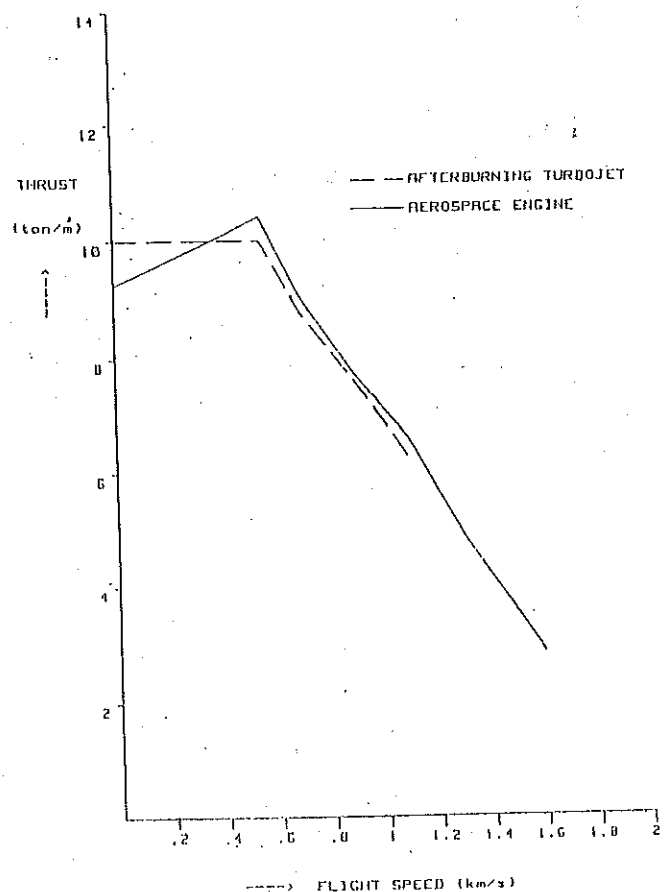


Fig. 6 Thrust characteristics

Gross propulsion characteristics of this unified aerospace engine is seen to be very promising in that specific impulse values much higher than other engine configurations are possible throughout the flight regime. This is a predominant factor for increasing the payload fraction of an aerospace launch. Thrust levels can be managed to be adequately high even at high altitudes. The enhanced engine performance is expected to give rise to large improvement in mission performance in terms of payload fraction and incremental velocity. In a mission analysis to determine this improvement the effect of variable geometry intake and nozzles on installed drag as well as the choice of mission profile will have their respective influence. The variable geometry is provided only in static components though these are to be operable in flight. An added attraction of this concept is in the fact that no technological limitation is foreseen in the realisation of this engine as a hardware. The performance has been evaluated based on component characteristics at already demonstrated levels.

Conclusion

For an earth orbit mission, airbreathing engines integrated with a chemical rocket would offer enhanced benefits. Such an airbreathing engine should have optimised thrust and specific impulse characteristics throughout the mission profile of a space vehicle in order to maximise the payload capacity. This demands a flexible mixed mode of operation combining high by-pass fan turbo ramjet with afterburning turbojet. A new concept of interactive by-pass with interstage reheat which will fit those requirements has been proposed here to visualise a unified airbreathing engine. Preliminary evaluation of this concept is very promising in achieving a significantly higher specific impulse and thrust at the crucial stage of take off and supersonic climb through the atmosphere. Development of this new concept into a practical aerospace engine will find useful application in the area of aerospace propulsion.

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